## ELECTROWEAK BARYOGENESIS FROM PREHEATING

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The origin of the matter-antimatter asymmetry remains one of the most fundamental problems of cosmology. In this talk I present a novel scenario for baryogenesis at the electroweak scale, without the need for a first order phase transition. It is based on the out of equilibrium resonant production of long wavelength Higgs and gauge configurations, at the end of a period of inflation, which induces a large rate of sphaleron transitions, before thermalization at a temperature below critical.

## 1 Introduction

Everything we see in the universe, from planets and stars, to galaxies and clusters of galaxies, is made out of matter, so where did the antimatter in the universe go? Is this the result of an accident, a happy chance occurrence during the evolution of the universe, or is it an inevitable consequence of some asymmetry in the laws of nature? Theorists tend to believe that the observed excess of matter over antimatter,  $\eta = (n_{\rm B} - n_{\rm \bar{B}})/n_{\gamma} \sim 10^{-10}$ , comes from tiny differences in their fundamental interactions soon after the end of inflation. It is known since Sakharov that there are three necessary conditions for the baryon asymmetry of the universe to develop. First, we need interactions that do not conserve baryon number B, otherwise no asymmetry could be produced in the first place. Second, C and CP symmetry must be violated, in order to differentiate between matter and antimatter, otherwise B non-conserving interactions would produce baryons and antibaryons at the same rate, thus maintaining zero net baryon number. Third, these processes should occur out of thermal equilibrium, otherwise particles and antiparticles, which have the same mass, would have equal occupation numbers and would be produced at the same rate. The possibility that baryogenesis could have occurred at the electroweak scale is very appealing. The Standard Model is baryon symmetric at the classical level, but violates B at the quantum level, through the chiral anomaly. Electroweak interactions violate C and CP through the irreducible phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix, but the magnitude of the violation is probably insufficient to account for the observed baryon asymmetry.<sup>2</sup> This failure suggests that there must be other sources of CP violation in nature. Furthermore, the electroweak phase transition is certainly not first order and is probably too weak to prevent the later baryon washout. In order to account for the observed baryon asymmetry, a stronger deviation from thermal equilibrium is required. An alternative proposal is that of leptogenesis,<sup>3</sup> which may have occurred at much higher energies, and later converted into a baryon asymmetry through non-perturbative sphaleron processes at the electroweak scale.

Recently, a new mechanism for electroweak baryogenesis was proposed,<sup>4</sup> based on the non-perturbative and out of equilibrium production of long-wavelength Higgs and gauge configurations via parametric resonance at the end of inflation.<sup>a</sup> Such mechanism occurs very far from equilibrium and can be very efficient in producing the required sphaleron transitions that gave rise to the baryon asymmetry of the universe, in the presence of a new CP-violating interaction, without assuming that the universe ever went through the electroweak phase transition.

# 2 The hybrid model

The new scenario<sup>4</sup> considers a very economical extension of the symmetry breaking sector of the Standard Model with the only inclusion of a singlet scalar field  $\sigma$  that acts as an inflaton.<sup>b</sup> Its vacuum energy density drives a short period of expansion, diluting all particle species and leaving an essentially cold universe, while its coupling to the Higgs field  $\phi$  triggers (dynamically) the electroweak symmetry breaking. After inflation, the coherent inflaton oscillations induce explosive Higgs production, via parametric resonance.<sup>6,7</sup>

As a toy model, we consider a hybrid model of inflation at the electroweak scale. The resonant decay of the low-energy inflaton can generate a high-density Higgs condensate characterized by a set of narrow spectral bands in momentum space with large occupation numbers. The system slowly evolves towards thermal equilibrium while populating higher and higher momentum modes. The expansion of the universe at the electroweak scale is negligible compared to the mass scales involved, so the energy density is conserved, and the final reheating temperature  $T_{\rm rh}$  is determined by the energy stored initially in the inflaton field. For typical model parameters<sup>4</sup> the final thermal state has a temperature below the electroweak scale,  $T_{\rm rh} \sim 70~{\rm GeV} < T_c \sim 100~{\rm GeV}$ . Since  $T_{\rm rh} < T_c$ , the baryon-violating sphaleron processes, relatively frequent in the non-thermal condensate, are Boltzmann suppressed as soon as the plasma thermalizes via the interaction with fermions.

 $<sup>^</sup>a\mathrm{A}$  similar idea, based on topological defects,  $^5$  was proposed at the same time.

 $<sup>^{</sup>b}$ This field is not necessarily directly related to the inflaton field responsible for the observed temperature anisotropies in the microwave background.

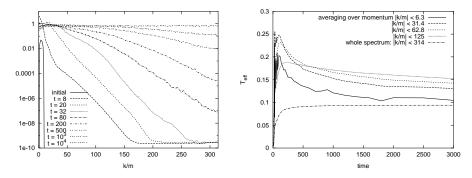


Figure 1. The left panel shows the evolution of the Higgs spectrum  $n_k \, \omega_k$ , in units of v=246 GeV, from time 0 to  $10^4 \, v^{-1}$ , as a function of momentum, k/m. The initial spectrum is determined by parametric resonance, and contains a set of narrow bands (solid line). The subsequent evolution of the system leads to a redistribution of energy between different modes. Note how rapidly a "thermal" equipartition is reached for the long-wavelength modes. The right panel shows the time evolution of the effective temperature  $T_{\rm eff}$  in units of v. Note the smooth rise and decline of the effective temperature with time.

One of the major problems that afflicted previous scenarios of baryogenesis at the electroweak scale is the inevitability of a strong wash-out of the generated baryons after the end of the CP-violation stage during the phase transition. This problem was partially solved in the new scenario, where CP violation and efficient topological (sphaleron) transitions coexist on roughly the same time scale, during the resonant stage of preheating, while afterresonance transitions are rapidly suppressed due to the decay of the Higgs and gauge bosons into fermions and their subsequent thermalization below 100 GeV. For example, for the electroweak symmetry breaking VEV v=246GeV, a Higgs self-coupling  $\lambda \simeq 1$ , and an inflaton-Higgs coupling  $g \simeq 0.1$ , we find a negligible rate of expansion during inflation,  $H \simeq 7 \times 10^{-6}$  eV, and a reheating temperature  $T_{\rm rh} \simeq 70$  GeV. The relevant masses for us here are those in the true vacuum, where the Higgs has a mass  $m_{\rm H} = \sqrt{2\lambda} v \simeq 350$ GeV, and the inflaton field a mass  $m = gv \simeq 25$  GeV. Such a field, a singlet with respect to the Standard Model gauge group, could be detected at future colliders because of its large coupling to the Higgs field.

One of the most fascinating properties of rescattering after preheating is that the long-wavelength part of the spectrum soon reaches some kind of local equilibrium,<sup>8</sup> while the energy density is drained, through rescattering and excitations, into the higher frequency modes. Therefore, initially the low energy modes reach "thermalization" at a higher effective temperature, see

Fig. 1, while the high energy modes remain unpopulated, and the system is still far from true thermal equilibrium. Thus, for the long wavelength modes,  $n_k = [\exp(\omega_k/T) - 1]^{-1} \sim T_{\rm eff}/\omega_k \gg 1$ , and the energy per long wavelength mode is then  $E_k \approx n_k \omega_k \approx T_{\rm eff}$ , or effectively equipartitioned. Since energy is conserved during preheating, and only a few modes  $(k \le k_{\rm max} \sim 10 \, m)$  are populated, we can compute the energy density in the Higgs and gauge fields, to give, 4 in (3+1)-dimensions,  $(10/6\pi^2)T_{\rm eff}k_{\rm max}^3 = \lambda v^4/4$ , or

$$T_{\rm eff} \simeq 350 \text{ GeV} \approx 5 T_{\rm rh} \,.$$
 (1)

The temperature  $T_{\rm eff}$  is significantly higher than the final reheating temperature,  $T_{\rm rh}$ , because preheating is a very efficient mechanism for populating just the long wavelength modes, into which a large fraction of the original inflaton energy density is put. This means that a few modes carry a large amount of energy as they come into partial equilibrium among themselves, and thus the effective "temperature" is high. However, when the system reaches complete thermal equilibrium, the same energy must be distributed between all the modes, and thus corresponds to a much lower temperature.

# 3 Baryon asymmetry of the universe

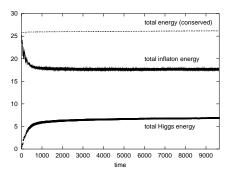
The Higgs and gauge resonant production induces out of equilibrium sphaleron transitions. Sphalerons are large extended objects sensitive mainly to the infrared part of the spectrum. We conjectured<sup>4</sup> that the rate of sphaleron transitions at the non-equilibrium stage of preheating after inflation could be estimated as  $\Gamma_{\rm sph} \approx \alpha_{\rm w}^4 T_{\rm eff}^4$ , where  $T_{\rm eff}$  is the effective temperature associated with the local "thermalization" of the long wavelength modes of the Higgs and gauge fields populated during preheating.

In the Standard Model, baryon and lepton numbers are not conserved because of the non-perturbative processes that involve the chiral anomaly:

$$\partial_{\mu} j_{\scriptscriptstyle B}^{\mu} = \partial_{\mu} j_{\scriptscriptstyle L}^{\mu} = \frac{3g_{\scriptscriptstyle W}^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu} \,. \tag{2}$$

Moreover, since sphaleron configurations connect vacua with different Chern-Simons numbers,  $N_{\rm \tiny CS}$ , they induce the corresponding changes in the baryon and lepton number,  $\Delta B = \Delta L = 3\Delta N_{\rm \tiny CS}$ .

A baryon asymmetry can therefore be generated by sphaleron transitions in the presence of C and CP violation. There are several possible sources of CP violation at the electroweak scale. The only one confirmed experimentally is due to CKM mixing of quarks that introduces an irreducible CP-violating phase, which is probably too small to cause a sufficient baryon asymmetry.



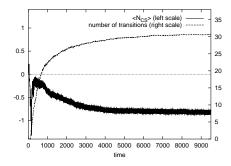


Figure 2. The left panel shows the time evolution of the inflaton and Higgs energies in the case of a low energy resonance. The Higgs acquires here only about a third of the initial energy, while the inflaton zero-momentum mode retains the remaining two thirds. The right panel shows the continuous production of baryons as a result of correlations between the topological transition rate and the CP-violating operator in the Lagrangian. For a detailed description see Refs. [4,9]. The solid line represents the shift in the Chern-Simons number,  $N_{\rm CS}$ , averaged over an ensemble of a few hundred independent runs. The dashed line is the integral  $\int \Gamma_{\rm sph} dt$ , i.e. the average number of topological transitions accumulated per individual run. Note the remarkable similarity of both curves for t>1000. This means that all transitions at this stage are equally efficient in generating baryons, changing the Chern-Simons number by about -1/20 per transition for many oscillations, demonstrating the absence of baryon wash-out in the model.

Various extensions of the Standard Model contain additional scalars (e.g. extra Higgs doublets, squarks, sleptons, *etc.*) with irremovable complex phases that also lead to C and CP violation.

We are going to model the effects of CP violation with an effective field theory approach. Namely, we assume that, after all degrees of freedom except the gauge fields, the Higgs, and the inflaton are integrated out, the effective Lagrangian contains some non-renormalizable operators that break CP. The lowest, dimension-six operator of this sort in (3+1) dimensions is<sup>9</sup>

$$\mathcal{O} = \frac{\delta_{\rm CP}}{M_{\rm new}^2} \phi^{\dagger} \phi \, \frac{3g_W^2}{32\pi^2} \, F_{\mu\nu} \tilde{F}^{\mu\nu} \,. \tag{3}$$

The dimensionless parameter  $\delta_{\text{CP}}$  is an effective measure of CP violation, and  $M_{\text{new}}$  characterizes the scale at which the new physics, responsible for this effective operator, is important. Of course, other types of CP violating operators are possible although, qualitatively, they lead to the same picture.<sup>4</sup>

If the scalar field is time-dependent, the vacua with different Chern-Simons numbers are not degenerate. This can be described quantitatively in terms of an effective chemical potential,  $\mu_{\rm eff}$ , which introduces a bias between baryons and antibaryons,  $^4$   $\mu_{\rm eff} \simeq \delta_{\rm CP} \, \frac{d}{dt} \langle \phi^\dagger \phi \rangle / M_{\rm new}^2$ . Although the system is very far from thermal equilibrium, we will assume that the evolution of the baryon number  $n_{\rm B}$  can be described by a Boltzmann-like equation, where only the long-wavelength modes contribute,  $\dot{n}_{\rm B} = \Gamma_{\rm sph} \, \mu_{\rm eff} / T_{\rm eff} - \Gamma_{\rm B} \, n_{\rm B}$ , with  $\Gamma_{\rm B} = (39/2) \Gamma_{\rm sph} / T_{\rm eff}^3 \sim 20 \, \alpha_{\rm w}^4 T_{\rm eff}$ . The temperature  $T_{\rm eff}$  decreases with time because of rescattering, see Fig. 1. The energy stored in the low-frequency modes is transferred to the high-momentum modes.

The rate  $\Gamma_{\rm B}$ , even at high effective temperatures, is much smaller than other typical scales in the problem. Indeed, for  $T_{\rm eff} \sim 400~{\rm GeV}$ ,  $\Gamma_{\rm B} \sim 0.01~{\rm GeV}$ , which is small compared to the rate of the resonant growth of the Higgs condensate. It is also much smaller than the decay rate of the Higgs into W's and the rate of W decays into light fermions. Therefore, the last term in the Boltzmann equation never dominates during preheating and the final baryon asymmetry can be obtained by integrating the Boltzmann equation

$$n_{\rm B} = \int dt \, \Gamma_{\rm sph}(t) \frac{\mu_{\rm eff}(t)}{T_{\rm eff}(t)} \simeq \Gamma_{\rm sph} \, \frac{\delta_{\rm CP}}{T_{\rm eff}} \, \frac{\langle \phi^{\dagger} \phi \rangle}{M_{\rm new}^2} \,, \tag{4}$$

where all quantities are taken at the time of thermalization. This corresponds to a baryon asymmetry

$$\frac{n_{\rm B}}{s} \simeq \frac{45\alpha_{\rm w}^4 \delta_{\rm CP}}{2\pi^2 g_*} \frac{\langle \phi^{\dagger} \phi \rangle}{M_{\rm pew}^2} \left(\frac{T_{\rm eff}}{T_{\rm rh}}\right)^3,\tag{5}$$

where  $g_* \sim 10^2$  is the number of effective degrees of freedom that contribute to the entropy density s at the electroweak scale. Taking  $\langle \phi^{\dagger} \phi \rangle \simeq v^2 = (246 \, {\rm GeV})^2$ , the scale of new physics  $M_{\rm new} \sim 1 \, {\rm TeV}$ , the coupling  $\alpha_{\rm w} \simeq 1/29$ , the temperatures  $T_{\rm eff} \simeq 350 \, {\rm GeV}$  and  $T_{\rm rh} \simeq 70 \, {\rm GeV}$ , we find

$$\frac{n_{\rm B}}{s} \simeq 3 \times 10^{-8} \, \delta_{\rm CP} \, \frac{v^2}{M_{\rm new}^2} \left(\frac{T_{\rm eff}}{T_{\rm rh}}\right)^3 \simeq 2 \times 10^{-7} \, \delta_{\rm CP} \,,$$
(6)

consistent with observations for  $\delta_{\rm CP} \simeq 10^{-3}$ , which is a typical value from the point of view of particle physics beyond the Standard Model. Therefore, baryogenesis at preheating can be very efficient in the presence of an effective CP-violating operator coming from some yet unknown physics at the TeV scale.

An important peculiarity of the new scenario is that it is possible for the inflaton condensate to remain essentially spatially homogeneous for many oscillation periods, even after the Higgs field has been produced over a wide spectrum of modes. These inflaton oscillations induce a coherent oscillation of the Higgs VEV through its coupling to the inflaton, and thus induce CPviolating interactions arising from operators (3) containing the Higgs field. These oscillations affect the sphaleron transition rate  $\Gamma_{\rm sph}$  as well, since the Higgs VEV determines the height of the sphaleron barrier, therefore producing strong time correlations between variations in the rate  $\Gamma_{\rm sph}$  and the sign of CP violation.<sup>12</sup> It is this correlation between CP violation and the growth in the rate of sphaleron transitions which ensures that the baryonic asymmetry generated is completely safe from wash-out, because of the long-term nature of CP oscillations. Depending on initial conditions, the rate  $\Gamma_{\rm sph}$  can finally vanish, e.g. due to the (bosonic) thermalization of the Higgs field, as seen in Fig. 2, but this doesn't affect the continuous pattern of CP- $\Gamma_{\rm sph}$  correlations. In other words, these correlations effectively give rise to a permanent and constant CP violation, thus preventing the generated asymmetry from being washed out.<sup>12</sup>

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